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A REVIEW OF RESEARCH ON FLASH BLINDNESS

by

J. D. Teresi

U.S. NAVAL RADIOLOGICAL DEFENSE LABORATORY

SAN FRANCISCO · CALIFORNIA · 94135

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ABSTRACT

The nature and cause of flash blindness are briefly discussed, and the most important data from both field tests and laboratory experiments are summarized. Data on time of recovery from effects of flash blindness are reviewed and presented as a function of total effective integrated energy in the flash, the size of the pupil, the state of adaptation prior to the flash, the size of the critical detail in the recovery target, the luminance of the target, the spectrum of the radiation, and individual variation in response.

From a military operational point of view, this survey indicates that there is sufficient data on basic phenomena to proceed to research on possible countermeasure devices.

SUMMARY

Published data on flash blindness from field tests and laboratory experiments have been summarized. The laboratory research results are presented for both low and high intensity flashes. A number of reports on low intensity flashes are referenced in this report with little discussion since the studies generally employed bleaching light intensities much lower than may be produced by nuclear weapons. However, observations of the effects of lower intensity flashes may help in understanding higher intensity phenomena. Results of low light intensity experiments on the effect of age on dark adaptation and critical flicker fusion frequencies showed that in flicker as well as in dark adaptation, the increase in threshold luminance is not a linear function of age, but that at about the age of 40 a sudden acceleration in sensitivity to glare occurs.

A relationship was obtained from 194 cases (20 to 60 years of age) which states that for every increase of 13 years in age, intensity of illumination must be doubled to be just seen by the fully dark adapted eye.

On the basis of experiments employing high light intensity, it was concluded that recovery times depend upon total effective integrated energy in the flash, the size of the pupil, the state of adaptation prior to the flash, the size of the critical detail in the recovery target, the luminance of the target, the spectrum of the radiation and

individual variation in response. The results of various studies are listed below:

1. The only portion of flash radiation that influenced the recovery times for foveal performance was in the visible region. Infrared had no effect on prolonging the recovery time following the flashes, even when it accounted for more than 50% of the total flash energy.

2. There was a small but statistically significant effect on foveal recovery for different flash-field diameters for 2.5° to 10°, with the smaller fields producing longer recovery times.

3. An approximately linear relationship was found between the logarithm of retinal illuminance times the duration of the flashes and logarithm of the recovery times for the recognition of a 20/60 acuity target at 0.06 millilambert, over the range of 20 seconds to 130 seconds recovery time, corresponding to a range of 9×10^5 to 3×10^7 troland-seconds flashes.

4. There was no significant cumulative effect on recovery times with successive flashes after the second flash when they were presented at intervals of three or four minutes. The first flash in a series produced a slighly shorter recovery period than the following flashes.

5. The recovery times following a flash depend upon the type of target used for measuring visual performance. There was a linear relationship between the logarithms of the recovery time and the visual acuity for different size test letters, expressed as the reciprocals of the visual angle subtended.

6. The variation between individuals exposed to flash was found to be large. There was a factor of about 2 between the means of the highest recovery time and lowest recovery time.

7. There is some indication that vision through narrow spectral band eye-protective filters may be possible while the eyes sensitivity in other spectral regions is relatively preserved after intense flash. Further studies are required to extend the findings to various wavelengths not already considered and to different durations of adapting stimuli, covering the range up to those intensities that produce irreversible retinal disorder.

An examination of data from field experiments led to the conclusion that since appreciable thermal energy continues to be radiated after the minimum blink reflex time, for atmospheric bursts greater than about 5-10KT, individual differences in blink response may influence the results. Those experiments in which shutters were employed provide results that are consistent with the laboratory findings. As in the laboratory experiments, considerable variation in recovery between subjects was found. In addition, variation in recovery was found in the same individual from one test to another under comparable conditions.

The minimum information about a weapon flash necessary for research and development purposes in regards to the problem of flash blindness appears to be luminance, duration and visual angle subtended by the source whether it is a fireball or a surface illuminated by the fireball. A discussion of the estimation of these parameters from information

given in Effects of Nuclear Weapons (1) is presented. From the estimates presented it appears that the integrated luminance received from a surface with 10% diffused reflectance from a 5-10KT low altitude burst can be over 5 log mL-sec if no protective measures but the blink reflex is used. This luminance is sufficient to cause flash blindness hazardous to pilots. The luminance of a fireball viewed directly can be as much as four orders of magnitude greater.

From a military operational point of view, the conclusion that can be drawn from this survey is that any further investigation on the flash blindness problem should be justified in terms of studies designed to develop protective devices based on the findings which indicated that sensitivity might be preserved in parts of the spectrum, while permitting continuous viewing through special eye-protective filters. Experiments designed to refine the results of basic phenomena already published do not seem justified.

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1. Introduction

A status report of the currently available information on personnel injuries from thermal radiation useful in evaluating the thermal hazards from Nuclear Weapons is of importance in shaping future research requirements in areas of military importance. In this study, information has been gathered on one of the effects of thermal radiation, namely, flash blindness (temporary loss of visual function). The nature and cause of this effect are briefly discussed and the most important data from both field and laboratory experiments are summarized.

2. Nature and Cause of Flash-blindness

According to Effects of Nuclear Weapons (1), temporary flash blindness or "dazzle" results when more thermal energy is received on the retina than is necessary for image perception, but less then is required for burn. The effect is a localized bleaching of the visual elements, with image persistence, after-image formation, halo, etc. From a few seconds to several days may be required for the eye to recover its functions. Dazzle is essentially the same as flash blindness although some authorities reserve the term "dazzle" for the effect of scattered light reaching the eye in which recovery is much more rapid than with "line of sight" flash blindness. Flash blindness occurs at greater ranges at night when the eye is dark adapted, than in daylight; however the range of these effects is highly dependent on atmospheric conditions prevailing at the time of detonation.

In discussing flash blindness Gulley, et al (2) stated that three

factors contribute to the lowering of visual acuity following exposure of the eye to high-intensity light. These are glare from the light source, bleaching of the photochemical substances within the rods and cones of the retina with the resultant time interval necessary for readaptation, and after images.

2.1. Glare. This was defined (3) as any degree of light falling upon the retina in excess of that which enables one to see clearly; that is to say, any excess of light which hinders instead of helps vision. Glare is differentiated into: (1) veiling glare, created by light uniformly superimposed on the retinal image which reduces contrast and therefore visibility; (2) dazzling glare, adventitious light scattered in the ocular media so as not to form part of the retinal image; and (3) scotomatic (blinding) glare, produced by light of sufficient intensity to reduce the sensitivity of the retina and corresponding to heavy overexposure in photography (4).

Although all these types of glare are present in the case of high-intensity light, the effects of the first two are primarily evident, only while the source is present. The third type is especially significant because it gives rise to those symptoms which persist long after the light source itself has vanished.

2.2. Adaptation. A change produced in a retinal area which can be traced to the after effects of previous stimulation is termed adaptation. When the eye becomes attuned to bright light, it is said to be light adapted; when it is attuned to low levels of illumination,

it is said to be dark adapted. Vision in these two states shows fundamental differences. The change from one state to another is not instantaneous. Instead a definite time interval, dependong on the direction and extent of change in adaptation desired is required. Re-adaptation times to a previous level of adaptation after exposure to the intense light of various sources are desirable experimental endpoints.

Adaptation of the retina after exposure to white light varies considerably with the area of the retina considered. The sensitivity of the peripheral retina may be increased from 50,000 to 100,000 times and this process requires as much as 30 minutes before full adaptation is approached. The increase in sensitivity of the fovea (central retina) with dark adaptation is relatively small, compared with that of the peripheral retina. The increase in foveal sensitivity with dark adaptation is only 10 to 20 times that of the light-adapted fovea and the time interval required for adaptation is 5 to 8 minutes.

In practice, only recovery of useful foveal vision may be required, for example pilots exposed to intense light need only to recover this vision to read aircraft instruments necessary in continuing the mission (2). Lohman (4) has shown that foveal dark adaptation is lost with extreme rapidity on exposure to bright light. Foveal readaptation to low levels of illumination is known to be relatively fast. Use of high-intensity instrument lighting will decrease the time interval between exposure of the eye to a flash of light and the return to useful vision.

2.3. After Images: The after image is a prolongation of the physiological process that produced the original sensation response after cessation of stimulation. If similar in nature to the original sensation, it is called a positive after image. Thus, if the eye is fixed upon the light for a time and then the light is turned off, an image can still be seen. Ordinarily, the sequence of events following stimulation of the retina by a flash of light is the primary sensation of light followed by a series of positive and negative after images. With moderate, light intensities, after images are not noticed because of the complex action of successive stimulation and continuous movement of the eyes. However, if the original stimulation is of sufficient duration and intensity, the sensation will persist with an intensity adequate to reduce or entirely obliterate foveal perception until the effect is dissipated. The time relation of recovery from after images is also a desirable experimental endpoint. In general terms, at the fovea, the latent period varies inversely, and the duration of the after image directly with the duration of the primary stimulus up to a limit of fixation of one minute.

3. Laboratory Research.

3.1. Low Intensity Flashes. Classical dark adaptation studies generally employed light intensities much lower than may be produced by nuclear weapons. However, observations of the effects from these flashes may be useful in understanding the effects from high intensity flashes. Numerous studies have been published which described

adaptation to low light levels (5, 6, 7, 8, 9, 10, 11, 12). Among the results applicable to an understanding of high intensity effects are those of Crawford (6) Barlow and Sparrock (12) McFarland and Fisher (9) and McFarland et al (10).

One of the most productive means of describing flash blindness is to employ Crawford's "equivalent background" concept, which is based on the transformation of the recovery curve of thresholds against time into one of equivalent background against time. This transformation was done by measuring the required brightness of a steady background for threshold visiblity of a test object, plotting a threshold versus background brightness curve and then substituting the equivalent background values for thresholds in the original threshold-time curve. Curves of threshold versus background brightness have been measured for a variety of test stimuli, and the resulting curves relating equivalent background with time after a flash were found to be independent of the test stimulus parameters. For example, predictions based on data obtained with a test object subtending a 0.5° visual arc were found to correspond closely to measured recovery from flashes when observing landscape scenes, a zeppelin against the coulds over Hamburg harbor, and other scenes.

A number of experiments on the effect of age on dark adaptation are of particular importance to the study of rate of recovery from extremely bright light flashes. The most important of these are described here.

Robertson and Yudkin (13) studied the variation in dark adaptation with age, as measured by the final rod threshold attained, in a group of 758 English factory workers (ages 14 to 74 years). The marked differences observed in maximum light thresholds in relation to age were attributed to the diminished pupil size in the elderly subjects. Birren (14) found in a study of 222 subjects (20 - 89 years of age) significant restrictions in pupil size with age in both light and dark conditions. McFarland and Fisher (9) studied 201 males between the ages of 20 and 60 years. Results on a group of 188 varying from 20 to 47 years of age showed that the difference between the final log reading (dark adaptation threshold) for the 20-24 year age group and the 40-47 year age group was 0.40 of a log unit. This represents an increase in the intensity of illumination required by the 40-47 year age group of about 150 percent. A relationship was obtained on 194 of the 201 cases chosen for testing (20 to 60 years of age) which states that for every increase of 13 years in age, intensity of illumination must be doubled to be just seen by the fully dark adapted eye.

Hecht and Mendelbaum (15) had obtained similar results earlier. In these studies and those of McFarland and Fisher described above, the size of the pupil was controlled with a 3-mm pupillometer, indicating an age effect not attributable to pupil size.

The effect of scotomatic glare on observers of various age groups was studied by Wolf (11) using a glare source of high luminance and an angular subtense of 2 degrees at the center of a circular test field.

At various distances and in different radial directions from the source as center were exhibited visual targets for identification. The author reported the results obtained with 112 individuals varying in age between 5 and 85 years. When the glare luminance was varied between 1 and 15,000 mL (millilamberts), the luminance of the target screen on which the Landolt rings were presented had to be increased proportionally. This increase necessary for the recognition of the targets became progressively greater as age increased. Comparing individuals in the age range between 5 and 15 years with those in the range between 75 and 85 years, a 50 to 70 fold increase in target screen luminance was necessary for the latter group as compared with the former. At the age of 40 years a sudden acceleration in sensitivity to glare occurred.

Changes in visual function in relation to age have also been described by Simonson, Enzer and Blankstein (16) and by Brozek and Keys (17) in studies on critical flicker fusion frequencies (CFF). Above the age of 40 a decrease in CFF was observed. Misiak (18) found a regular decline in CFF with age in the range from 20 to 89 years. Copinger (19) determined that the relationship between CFF and age is linear over the range between 20 and 90 years. That this cannot be due to decrease in pupillary size was shown by Weekers and Roussel (20), who after dilatation with atropine still found a decline of CFF with age. McFarland, Warren and Karis (21) studied CFF while the ratio of light-time to dark-time in the flicker cycle was varied from 2/98 to 98/2 for observers between 13 and 89 years of age. As in the cases above,

CFF was found to vary with age at all ratios, but the differentiation of CFF at various age levels is easier when the light-time fraction in each cycle is less than 50 percent.

Wolf (11) points out that in flicker as well as in dark adaptation studies, the increase in threshold luminance is not a linear function of age. In plotting CFF against age, the flicker data suggest a change in slope between 40 and 45 years and the dark adaptation data show an accelerated increase in threshold values above the age of 40 when final rod levels (taken at 40 minutes of dark adaptation) are plotted against age. These observations strongly support the findings of Wolf (11) that above the age of 40 years a rather abrupt increase in the effect of scotomatic glare occurs which decreases the ability to recognize targets in the vicinity of a glare source.

The dependence of flicker recognition, threshold excitability and glare sensitivity on age raises the question as to what specific changes in the visual mechanism could be the cause of an alteration in sensitivity. Changes in transmissiveness of the ocular media caused by various changes due to ageing are discussed by Wolf (11) who concludes that precise correlations between physical changes of media and retinal sensitivity do not exist.

Finally, Domey, McFarland and Chadwick (22) developed an empirical mathematical model for representing dark adaptation as a function of age and time from experimental data on 240 men ranging from 16 through 89 years. The authors also present a critical analysis of data

previously published. It was concluded that threshold of dark adaptation as a function of time was related to chronological age and that the rate of dark adaptation was a curvilinear function of age. The findings were consistent with the hypothesis that the thresholds and rate of dark adaptation depend upon basic underlying physiological processes that change with age.

3.2. High Intensity Flashes. Laboratory measurement of recovery of visual function after exposure to high intensity flashes have been reported, the most pertinent of which are summarized here.

Several investigators have undertaken basic research on effects of absorption of light energy by the eye at levels below threshold for chorioretinal burns. Whiteside (23, 24) attempted to simulate the dazzling effect of an atomic explosion at night using the sun as a light source. Comparison of recovery times appears in Fig. 1 along with other data. When the integrated stimulus intensity exceeded about $3X10^7$ mL-sec, the recovery times increased rapidly. This dose was received during a 2-second exposure to the solar disc and produced an after image which persisted for a week to ten days. It is therefore probable that mild retinal damage was produced by this dose.

The time required to recover visual sensitivity following exposure to high-intensity short-duration adapting flashes was measured by Chisum et al (25) and Hill and Chisum (26) using adapting flashes of 33 and 165 microseconds and 9.8 milliseconds in duration with luminances

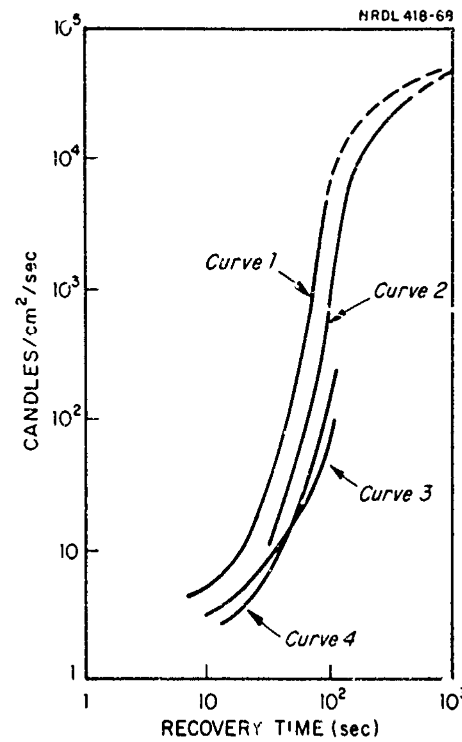

Fig. 1. Comparison of flash blindness recovery time in several experiments(from Whiteside, reference 24). Curve 1, recovery of daylight adapted eye to 0.14 ft-L after exposure to nuclear flash (upper point) or calibration source (lower points). Curve 2, recovery of dark adapted pupil to 0.03 ft-L after viewing solar disc. Curve 3, recovery to 0.07 ft-L after searchlight exposure (Metcalf and Horn, 27). Curve 4, recovery to 0.14 ft L (Crawford, 6).

up to 8.6 log mL. (Xenon-filled flash lamp). Visual sensitivity was determined by the resolution of gratings requiring acuities (reciprocal of visual angle in minutes) of 0.13 and 0.33 at display luminances from -2.50 to 2.25 log mL. Recovery time was found to decrease as display luminance increased. Recovery time increased (a) with increases in acuity level at display luminances below 0.5 log mL; and (b) with increases in either the luminance or the duration of the adapting flash.

Metcalf and Horn (27) reported an investigation on 4 subjects concerned with the effects of high intensity flashes on visual recovery using a carbon arc searchlight as a source. They studied the effects of light intensities ranging from 60 to over 12,000 lumens per square foot at the eye (pupil diameter controlled at 6 min.) extrapolated the data to the estimated retinal burn threshold, and found a maximal recovery time of 170 seconds to read normally red-lighted aircraft instruments A straight line relation between recovery time and logarithmic increase in illuminance was reported. The research efforts of Whiteside and Metcalf and Horn were hindered by the lack of a versatile, dependable light source that would provide the necessary intensity ranges. Therefore, Severin et al (28) described a modification of the Meyer-Schwickerath Zeiss light coagulator for research in the study of flash blindness and presented preliminary data to demonstrate the reliability of the method. In these studies four subjects were exposed to light flashes ranging over 5 levels of illuminance (o45 lux to 56,180 lux) delivered in 0.15 seconds. Recovery was measured as the

period of time required for the subject to regain sufficient visual discrimination to perceive testing luminances of 0.06 and 0.13 ft lamberts. The response to increasing intensity of the test dazzle was significantly different for the two testing luminances. This difference was due to time increasing more rapidly with changes in dazzle intensity for the duller patch than for the brighter. The results followed a pattern that would be anticipated from previous reports (23, 24, 27. (1) Recovery time increased with increasing intensity of the test flash. (2) The time of functional visual loss following a dazzle decreased by increasing the luminance of the task to be viewed. The significance of the results was confirmed by statistical analysis. The analysis also indicated that the variation within a subject's responses was within acceptable limits for biological experimentation. An uncontrolled variable in this study was the pupillary size. The left pupil was dilated with hydroxyamphetamine before testing and the pupillary aperture was measured after each test run. Measurements ranged from 7 to 10 mm. An extension of these studies was reported by these authors (29) using 15 more subjects (ages 23 to 42 years). These subjects were exposed to light flashes ranging over three levels of corneal illuminance: 86, 080 lux, 150,640 lux and 242,100 lux using testing luminances of 0.06 ft.-L and 0.013 ft.-L and using both dilated and constricted pupils.

The data indicated that a linear relationship between recovery time and flash intensity gives a satisfactory description of the results

over the range of intensities stated, however, the best fitting lines differ in slope, depending upon the subject and the pupil size. The slopes vary from subject to subject and the slope of the best fitting line is greater for the larger pupil than for the small pupil. This is true for both the 0.06 ft.-L testing patch and for the 0.013 ft.-L testing patch. It was found that two normal subjects may differ by as much as 30 seconds in their recovery from dazzling flash of 242,100 lux. Encounters with light fields of this intensity may occur in nuclear operations.

Absolute recovery times ranged among subjects from about 0.16 minutes to 0.4 minutes for the constricted pupil at the exposure intensity level of 242,100 lux and test patch illuminance of 0.06 ft-L. For the 0.013 ft-L testing patch illuminance, the recovery value varied among subjects from about 0.27 minutes to 1.1 minutes under the same conditions of pupil size and exposure intensity.

Severin et al (30) reported studies in forty additional subjects designed to verify several observations reported previously (29) and to determine the effect of photostress involving a large retinal area (retinal image of 8-1/2 mm). Their results demonstrated that: (1) a linear plot describes the relationship between time required for recovery and flash intensity over the range tested. (2) There is a significant difference in recovery rates between subjects. (3) Pupillary size has a significant effect upon the time required for recovery from dazzle. The authors report that since for a range of corneal

illuminances of 86,000 to 242,000 lux a linear relationship exists between intensity of photostress and the time required for recovery, it will be possible, in many instances, to predict the duration of visual embarrassment that will result from exposure to intense light fields in an operational situation if details of the nature of the photostress are supplied. However, if these estimates are to be made, it will probably be necessary to establish a baseline for the men who will be involved in order to establish their recovery rate, since individual variability is so great that general predictions are not reliable. These estimations should probably be made only for retinal illuminances that will allow interpolation from the experimental data and only for situations in which the retinal image is comparable to that with which investigators have experimented. Linear extrapolation to more intense flashes may not be accurate since recovery rate will probably change as the retinal burn threshold is approached.

The results of some of the studies presented above have been summarized by Williams and Duggar (34) who present a summary table in which the units in the original papers are converted to common units for purposes of comparing the data. This table is reproduced here as Table 1. It can be seen that there is some difficulty in comparing the results of the different investigations because the recovery times depend upon total effective integrated energy in the flash, the size of the pupil, the state of adaptation prior to the flash, the size of the critical detail in the recovery target, and the

time course of the flash luminance may also be a factor in recovery for flashes shorter than a few milliseconds.

A study was reported by Miller (35) in which a number of these variables were tested with college students in their early 20's. The effect of nonvisible radiation on the recovery time was tested by comparing the results for flashes containing a large quantity of infrared radiation with flashes of equal luminance from which the infrared was removed by filtering. The diameter of the flash field was varied from 20' to 10° visual angle. The pulse shape of the flash was held constant for all durations from 42 μ sec to 1.4 m sec. The pulse shape, or time course of flash luminance was trapezoidal with the risetime to maximum luminance equal to a constant luminance time and to the decay time. The recovery targets were varied in size and luminance to determine the characteristics of recovery as a function of target parameters.

The subjects used had visual acuity of 20/20 or better and had no color vision anomalies. They were dark adapted for 5 minutes prior to each session. The target letters were presented at one-second intervals and were viewed for 0.8 sec in each interval. The size of the target letters used were 4.4, 3.01, 2.14 and 1.71 mm.

At the peak of the flash the full luminance of the system was 1.71×10^5 C/cm^2 or 5.4×10^5 L. With a special filter the value was 4×10^5 L.

TABLE 1

Summary of Laboratory Studies of Flash Effects (from Reference 34)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec)	Number of Subjects	Visual Task and Luminance
28	64	150	9.6	7-10	a) 3-4 b) 7-9	4	25 mm target flashing on and off at 1 second intervals, luminance of; a) 0.06 mL b) 0.014 mL Target subtended 40' visual angle, was located 12° from fixation point (recovery times are ranges of means of five trials for each subject).
	5.4×10^2	150	81	7-10	a) 4-8 b) 9-18	4	
	10.8×10^2	150	1.6×10^2	7-10	a) 5-9 b) 16-26	4	
	2.7×10^3	150	4.0×10^2	7-10	a) 6-11 b) 19-37	4	
	5.62×10^3	150	8.4×10^2	7-10	a) 9-21 b) 31-52	4	
29	8.6×10^3	150	1.3×10^3	6-8.8 mean of 7.62	a) 6-18 mean 10 b) 9-33 mean 18	15 15	Same as 28 above.
				1-3.5 mean of 2.15	a) 6-12 mean 9 b) 11-28 mean 20	15 15	

Table 1 (continued)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec)	Number of Subjects	Visual Task and Luminance
29	1.5×10^4	150	2.3×10^3	6-8.8	a) 10-32 mean 17 b) 16-47 mean 28	15 15	Same as 28.
				1-3.5	a) 8-17 mean 12 b) 15-44 mean 28	15 15	
	2.4×10^4	150	3.6×10^3	6-8.8	a) 14-44 mean 28 b) 25-68 mean 44	15 15	Same as 28.
				1-3.5	a) 9-27 mean 17 b) 16-66 mean 37	15 15	
30	8.6×10^3	150	1.3×10^3	dilated	a) mean 16 c) mean 11	40 40	a) Same as 28, c) discrimination of Landolt C ring of 0.06 mL luminance.
	1.5×10^4	150	2.3×10^3	dilated	a) mean 26 c) mean 18	40	
	2.4×10^4	150	3.6×10^3	dilated	a) mean 38 c) mean 28	40 40	

Table 1 (continued)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec)	Number of Subjects	Visual Task and Luminance
27	5×10^6	100	5×10^5	6	a) 5 b) 12 c) 35 d) 93	4 4 4 4	Detect flashing of a circular patch (17 minutes of visual angle) with luminance of: a) 76 mL, b) 7.5 mL, c) 0.49 mL, and d) 0.08 mL.
31	1.34×10^4	900	1.2×10^4	5	0.13 vis. acuity a) 1 b) 1 c) 2 d) 3 e) 5	2 2 2 2 2 2	Resolution of a visual grating pattern (1° size) to 0.13 to 0.33 visual acuity when illuminated to a) 0.2 mL, b) 0.56 mL, c) 5.6 mL, d) 1.8×10^2 mL, and e) 1.8×10^4 mL.
					0.33 vis. acuity a) 1 b) 1 c) 3 d) 4 e) 6	2 2 2 2 2 2	
	5.4×10^4	900	4.9×10^4	5	0.13 vis. acuity a) 2 b) 2 c) 6 d) 9 e) 18	2	

Table 1 (continued)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec)	Number of Subjects	Visual Task and Luminance
31					0.33 vis. acuity	2	
					a) 2	2	
					b) 2	2	
					c) 6	2	
					d) 12	2	
					e) 17	2	
	1.1×10^5	900	9.7×10^4	5	0.13 vis.		
					a) 2	2	
					b) 3	2	
					c) 9	2	
					d) 19	2	
					e) 25	2	
					0.33 vis. acuity		
					a) 2	2	
					b) 3	2	
					c) 10	2	
					d) 13	2	
					e) 27	2	
32	1.7×10^4 (3.5° source)	30	5.2×10^2	--	15-20	--	
	9×10^3 (reflection from large plane)	30	2.7×10^2	--	2-3	--	Return of normal vision.

Table 1 (continued)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec)	Number of Subjects	Visual Task and Luminance
26	1.25×10^6	9.8	1.2×10^4	5	0.13 vis.ac.		Acuity grating with display luminance of: a) 0.01 mL, b) 0.03 mL, c) 1 mL, and d) 10 mL. Graph scales were such that recovery times are only approximate.
					b) 135	2	
					c) 15	2	
					d) 10	2	
					0.33 vis. ac.		
					b) 142	1	
					c) 15-20	3	
					d) 8-12	3	
	4×10^5	9.8	3.9×10^3	5	0.33 vis. ac.		
					b) 25	1	
					c) 7	1	
					d) 2	1	
	1.25×10^4	9.8	12	5	0.13 vis.ac.		
					a) 4	1	
					b) 2	2	
					0.33 vis.ac.		
					a) 19	1	
					b) 8-26	2	
					c) 2	3	
	4×10^8	0.165	6.6×10^4	5	0.13 vis.ac.		
					b) 110-150	2	
					c) 12-18	2	
					d) 8	2	

Table 1 (continued)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec)	Number of Subjects	Visual Task and Luminance
26					0.33 vis.ac.		
					b) 140-150	2	
					c) 18-30	3	
					d) 8-15	3	
	4×10^7	0.165	6.6×10^3	5	0.13 vis. ac.		
					a) 32	1	
					b) 20	2	
					c) 5	2	
					d) 2	2	
					0.33 vis. ac.		
					a) 140	1	
					b) 22	1	
					c) 5	3	
					d) 2	[illegible]	
	4×10^6	0.165	6.6×10^2	5	0.33 vis.ac.		
					a) 58	1	
					b) 12	1	
					c) 2	3	
	2×10^8	33×10^{-3}	6.6×10^3	5	0.13 vis.ac.		
					a) 65	1	
					b) 12	2	
					c) 5	2	
					0.33 vis.ac.		
					b) 45-90	2	
					c) 5-10	2	
					d) 2	2	

Table 1 (continued)

Ref.	Flash Intensity (mL)	Flash Duration (ms)	Total Exposure (mL-sec at corneal plane)	Pupil Diameter (mm)	Recovery Time (sec)	Number of Subjects	Visual Task and Luminance
26	2×10^{7}	33×10^{-3}	6.6×10^{2}	5	0.13 vis.ac. a) 5	 1	
					0.33 vis.ac. a) 25 b) 10-65 c) 2	 1 2 2	
33	4.4×10^{8}	0.042 to 1.4	1.85×10^{4} to 6.2×10^{5}	2 (artificial pupil)	Mean recovery time, 42 μsec flash, letter sizes 2.5° to 10° - 14.22 sec. With 1.4 msec flash, letter sizes 2.5° to 10°, mean recovery time 109.7 sec.	5	Test letter luminance 0.066 mL. Field size range 10.0° to 20' visual arc.

The effect of the nonvisible energy at wavelengths greater than 700 mμ on the recovery times following exposure durations of 0.56 m sec was studied using recovery targets of 2.14 mm letters at a luminance of 0.07 mL. The results seemed to be conclusive that only radiant energy that produces a temporary loss of visual performance is that portion of the spectrum which is visually effective. The maximum value in recovery time among individuals was about a factor of 2 greater than the minimum value. The results of this study are summarized in Table 2. The flash energies are given in troland-seconds.*

In the study of the field sizes and exposure duration, five field sizes were tested, 10.0°, 7.5°, 5.0°, 2.5°, and 20' using target letters of 16.3' size (i.e., the visual angle subtended was 16.3') at a luminance of 0.07 mL and using flashes of 4.0×10^5L. Five exposure durations were used, 0.04, 0.10, 0.24, 0.56 and 1.40 m sec. The authors felt that the data for the 20' field were more variable than for the larger fields because of the difficulty in maintaining accurate fixation prior to the flash and during the presentation of the test letters. The means for recovery time for the four larger fields increased as the duration increased as follows: 14.22, 27.89, 51.47, 74.19 and 109.71 seconds for the durations given above. The data also showed that the smaller fields produced longer recovery times. This is

*A troland is equal to 1 candle/m^2 or to 0.3142 mL and may be defined as the retinal illumination produced by viewing a surface of luminance of 0.1 mL through a pupil 2mm in diameter.

TABLE 2

The Effect of Removing the Infrared on the Recovery Times (sec) for 0.07 mL Test Letter Subtending a Visual Angle of 16.3'. Modified from Table 3 of Reference 35.

Subject	KG-3 Filter $9.8X10^6$ td-sec	Means	0.13 Neutral Density Filter $9.8X10^6$ td-sec	Means	No Filter $1.3X10^7$ td-sec	Means
J.C.	51.6		63.2		51.4	
	54.3	60.9	61.8	53.2	60.6	57.3
	80.3		42.3		58.0	
	57.5		42.1		59.3	
L.L.	118.0		75.3		110.6	
	101.3		94.7	95.0	127.6	141.4
	115.5	115.4	92.8		173.1	
	126.6		117.0		155.0	
D.H.	35.4		42.0		48.4	
	38.0	38.2	45.2	41.5	51.4	55.6
	40.1		40.4		61.9	
	39.1		38.3		60.7	
E.11	40.0		35.0		71.0	
	51.0		53.5	50.1	71.2	70.2
	52.0	49.4	61.[illegible]		70.7	
	54.7		50.3		67.8	
V.K.	56.4		68.4		57.7	
	66.5	62.9	64.6	65.0	64.8	67.8
	62.2		64.5		73.0	
	66.3		62.5		75.7	
Means	65.34		60.78		78.50	

in the opposite direction from what would be expected on the basis of the greater amount of flux at the cornea for the larger fields causing more light to be scattered into the fovea. However, the effect of field size is much smaller than the effect of flash duration.

Field sizes of 10.0°, 7.5°, 5.0°, 2.5° resulted in means of recovery times of 52.99, 54.00, 56.35 and 59.08 seconds.

In the determination of the relationship between recovery time and target size, the four letter sizes subtending visual angles of 42, 28.7, 20.4 and 16.3 min of arc were presented at a luminance of 0.07 mL. The 10° flash was used and all flashes had a 1.4 m sec duration. The flash luminances were varied by using neutral density filters in the flash beam. The peak luminances used were 4.0×10^5L, 1.48×10^5L, 6.6×10^4L and 3.0×10^4L. Four subjects participated. Sample recovery times were, for angular subtense 42', 28.4', 20.4', and 16.3', 58.9, 73.3, 90.1 and 123.1 seconds for the 4.0×10^5 flash. The corresponding recovery times for the 3×10^4L flash were 11.1, 13.3, 18.9 and 22.3 seconds. The data showed that there was a linear relationship between the logarithms of the recovery time and the visual acuity for different size letters, expressed as the reciprocal of the visual angle subtended. The results of these studies are plotted in Fig. 2 for the various flash energies in units of troland-seconds.

In the studies on the relationship between recovery time and target luminance, the target letters used were those giving an

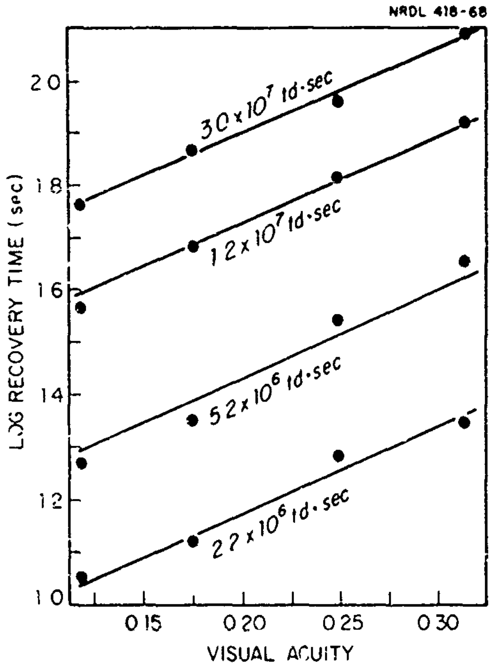

Fig. 2. The effect of target size on recovery time following various flash energies. The four test letters used subtended visual angles of 42',28.7',20.4', and 16.3'. The visual acuity is the reciprocal of the critical detail of the letters in min of arc.

angular subtence of 28.7' and 16.3' at luminances ranging from 131 mL to 0.07 mL following the highest flash energy. With the more rapid recovery following lower flash energies, correspondingly shorter ranges of target luminances were employed. Results for the 28.7' letter were reported by the authors showing the decrease in recovery time with increase in luminance of the letter. (Fig. 3). For the flash energy of 3.0×10^{7} td -sec the log recovery time (seconds) was 1.8 for a log luminance of letter of about -0.8 and 0.6 for log luminance of letter of about 2.2. At 5.2×10^{6} td-sec flash energy the log values of recovery times were 1.3 for log letter luminance of -0.8 and 0.8 for log letter luminance of -0.2. The results of the studies of Miller are summarized below.

1. The only portion of flash radiation that influenced the recovery times for foveal performance was in the visible region. Infrared had no effect on prolonging the recovery time following the flashes, even when it accounted for more than 50% of the total flash energy.

2. There was a small but statistically significant effect on foveal recovery for different flash-field diameters for 2.5^{o} to 10^{o}, with the smaller fields producing longer recovery times.

3. An approximately linear relationship was found between the logarithm of retinal illuminance times, the duration of the flashes, and the logarithm of the recovery times for the recognition of a 20/60 acuity target at 0.07 mL, over the range of 20 sec to 130 sec recovery time, corresponding to a range of 9×10^{5} to 3×10^{7} troland-sec flashes.

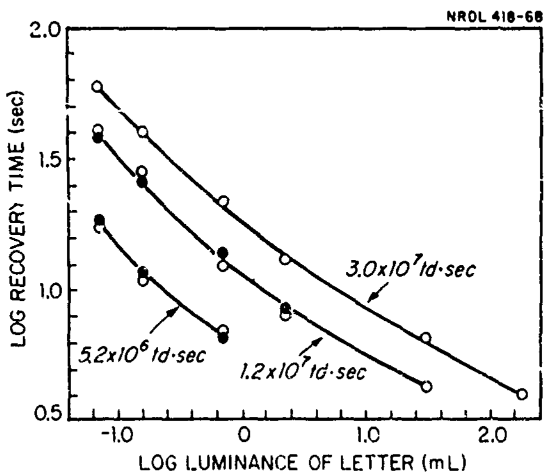

Fig. 3. The relationship between the logarithm of the recovery time and the logarithm of the test-letter luminance for different flash energies. The open circles are the data for 1.4-msec flashes of various luminances and the solid dots are the data for 4.0×10^5-L flashes of various durations.

4. There was no significant cumulative effect on recovery times with successive flashes after the second flash when they were presented at intervals of three or four minutes. The first flash in a series produced a slightly shorter recovery period than the following flashes.

5. The recovery times following a flash depend upon the type of target used for measuring visual performance. There was a linear relationship between the logarithms of the recovery time and the visual acuity for different size test letters, expressed as the reciprocals of the visual angle subtended.

The results presented in this report also show a variation in effects between subjects as shown in Table 2. There is a factor of about 2 between the means of the highest recovery time and the lowest recovery time. Additional studies showing the variations in effects between individuals were reported by Miller (36) (37). The results of these studies are shown in Fig. 4 taken from reference 36 and Table 3 taken from reference 37. Reference 37 used a test luminance as high as 140 mL.

In most studies reported in the literature broad spectral bands in the visible spectrum have been used. Little effort had been expended to study the adapting effects of intense, narrow spectral bands until Sperling (38) studied the effects of adaptation to spectral bands of light on human foveal spectral sensitivity. His results showed that where very narrow adapting bands in the upper range of intensities of normal vision are used, extreme changes in the shape of the

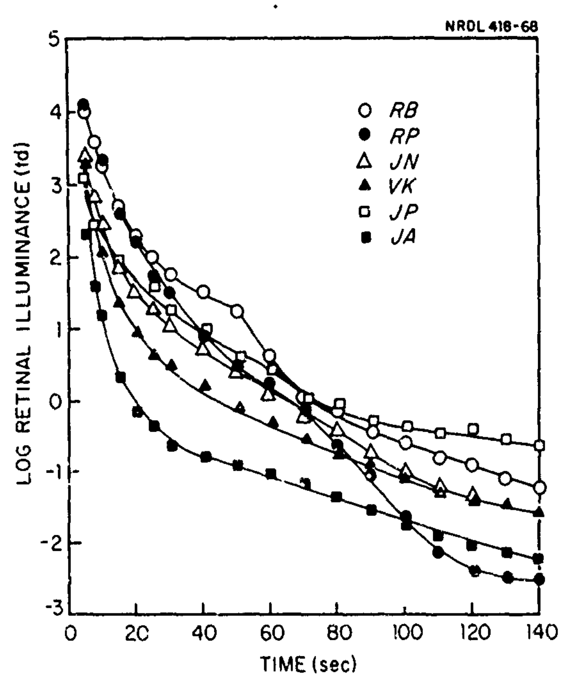

Fig. 4. The results for six subjects of afterimage brightness matching with a monocular bipartite field showing the large variation between subjects. The afterimages were formed by 0.56-msec flashes of 4 X 10^5-L.

TABLE 3. Recovery times for two letter sizes presented at various luminance levels following 1.4-msec flashes of 4×10^7 L. (from reference 37)

Log B of letter mL	J.N.	R.B.	D.P.	J. P.	J.A.	V.K.	Group mean
			28.7' Letter Subject				
2.15	8.0	4.5	7.5	7.5	8.5	4.0	6.66
1.45	13.5	7.5	11.0	13.0	13.0	8.0	11.00
0.73	22.5	12.0	14.0	19.5	17.0	13.0	16.33
0.29	25.0	16.5	18.0	23.0	20.5	17.0	20.00
-0.40	28.5	23.0	27.5	29.0	24.5	20.0	25.41
-0.83	31.5	27.5	44.5	33.5	35.5	25.0	32.91
-1.18	37.5	34.0	60.0	43.5	74.5	32.0	46.91
-1.53	43.5	37.5	95.0	61.0	94.0	41.0	62.00
-1.79	65.0	49.0	153.0	74.0	118.0	48.0	84.50
-2.14	101.0	62.5	198.5	107.5	226.0	57.0	125.41
			16.3' Letter				
2.15	4.0	5.0	10.0	6.5	5.0	6.0	6.08
1.45	12.0	10.0	18.0	10.5	8.5	10.0	11.50
0.73	19.0	13.5	25.5	14.5	13.0	15.0	16.75
0.29	27.0	18.0	38.0	21.5	18.5	19.0	23.66
-0.40	39.5	24.0	68.0	28.0	33.5	26.0	36.50
-0.83	52.0	36.0	92.5	32.0	47.5	47.0	51.16
-1.18	72.5	47.5	111.0	47.0	68.5	53.0	66.58
-1.53	81.0	73.5	178.0	69.0	124.0	73.0	99.75
-1.79	97.0	98.0	199.5	106.0	144.5	105.0	125.00
-2.14	137.0	119.0	308.0	164.5	...	160.0	177.70

sensitivity function results. This finding indicates that sensitivity might be preserved in parts of the spectrum, while permitting continuous viewing through special eye-protective filters. The results further indicated an approach to isolating the spectral response components of normal color vision and the magnitude of their response to light adaptation.

These studies were done on three subjects. Further studies might be carried out to extend the findings to various wavelengths not already considered and to different durations of adapting stimuli, covering the range up to those intensities that produce irreversible retinal disorders.

Further investigation of the possibility of applying the results of these studies to development of protective devices seem to be justified.

4. Field Experiments

Several measurements have been reported of exposure to the light from nuclear detonations. Byrnes (39) reported on field research conducted in Nevada to determine the duration of vision impairment that results from exposure to the flash of a nuclear burst during night operations. Observations were made of the effects at 10 miles distance of two daytime airbursts (30KT at 3447 ft and 19.6KT at 1040 ft) on eight subjects dark adapted in a light-tight trailer. Half the observers wore protective red goggles. The tests showed that recovery of useful vision for reading instruments, where both

red flood-lighting and internal red lighting were used, was rapid, with an average time of 23.3 sec for the unprotected eye, 8.8 sec for the protected eye. When only red internal lighting was used, the average time to the first correct reading was 105 seconds for the protected case. On the average the unprotected individuals tested regained sufficient vision to distinguish form or light at 0.001Nit* of illumination (approximately that of moonlight) in 310 sec; at 0.00001 Nit of illumination (approximately that of a clear starlit night) recovery times were 671 sec, unprotected, and 325 sec protected.

Results of field tests at Operation Upshot-Knothole reported by Byrnes et al. (40) were based on 12 subjects in a light-tight trailer exposed to 5 predawn nuclear detonation flashes at distances of 7 to 14 miles from bursts of 16 to 43 KT. Filters were used so that subjects were exposed to a narrow band of wavelengths between 600 and 900 mμ and the irradiation in the central image, formed at 10 miles distance from the fireball, during the first 1/10 second was reduced to 20-25% of the unfiltered irradiation. The period of exposure to the flash began at zero time and extended through the period of the blink reflex. The results on eight subjects (not always exactly the same list of subjects) showed that red-lighted instruments could be read correctly in an average of 18.4 seconds (range 5 to 27 seconds for all subjects for 5 shots) if illuminated with regulation type small red floodlights, and in an average of 55.9 seconds (range of 44 to 81 seconds) if illuminated with standard red internal lighting only. An important

* A Nit is a unit of luminance equivalent to 1 candle/m^2.

point to be noted is that there was considerable variation in recovery amongst the subjects as well as in the same individual from one test to another. For example, for shot 2 (24.5KT at 11 miles), one individual had recovery of 8 seconds, another of 15 seconds, and a third of 40 seconds while all others had recoveries of 20 to 25 seconds. Comparison of the results of the same subject for shot 2 and for shot 7 (43.4KT at 8 miles) showed recoveries of 40 seconds and 10 seconds respectively.

In addition, four subjects were tested on visual acuity testers for return of rod vision (low light-level vision for night situations). These tests indicated that recovery of the ability to distinguish light at 0.001 Nit of illumination occurred in an average of 160 seconds, at 0.00001 Nit illumination, in an average of 249 seconds. These times are about one half of those observed at Operation Snapper, for the unprotected subjects.

Whiteside (24) observed the first 102 milliseconds of a nuclear fireball, then measured the time to detect three test fields of different brightness. The total dose at the corneal plane was computed from calibrated film records. He compared the recovery times for foveal location of the image to that for a location 3° lateral to the fovea and found that the times were linearly related and nearly identical for discrimination of the test field through the afterimage.

Gulley et al. (2) have reported a series of field studies in which flash recovery times were measured at the Nevada test site. Their report was directed at determining the threat of flash blindness to tactical air operations. Four to eight subjects were exposed to three nuclear detonations, some with and others without protection devices. In addition, rabbits were exposed to five nuclear detonations. The following relationship between peak illuminance and peak thermal irradiance was derived: peak lumens/ft^2 = 3.8×10^5 x peak thermal irradiance (cal/cm^2-sec).

The protective shutters closed in 500 microseconds and had a 20% transmission when fully open. Experiments were run both with shutters operative and inoperative or with subjects behind a sandblasted window (diffusing screen). Visual recovery was measured with a nyctometer* with a background luminance of 0.4 mL, or by the ability to correctly read four aircraft instruments illuminated with standard Grimes edge lighting, as well as standard red flood lighting.

The results of these experiments have been summarized and tabulated by Williams and Duggar (34) and are reproduced here in Table 4.

Verheul, Lowry and Browning (41) described an experiment in which three groups of subjects were oriented at 90, 135 and 180 degrees from the line of sight to a fractional KT (1.2T) detonation at a distance of 5,700 ft. All 25 subjects were light adapted, unprotected by goggles and located slightly over a mile from the burst. Immediately after the shot, visual acuity was measured and visual targets identified.

* A nyctometer is an instrument designed to measure central visual acuity under controlled levels of background brightness.

TABLE 4 - From Williams and Duggar (34)

Flash Effects of Actual Nuclear Detonations

Ref.	Yield (KT)	Peak Luminance (mL)	Flash Duration (ms)	Total Energy at Corneal Plane	Pupil Diameter (mm)	Recovery Criteria and Procedures
24	--	1.4×10^8	100	1.4×10^7 mL-sec	4+	One subject viewed the fireball 3° off the fovea, then observed 1.1, 0.44, and 0.15 mL test fields. Foveal recovery times were 5, 17, and 58 seconds, respectively. Recovery times through the afterimage were 28, 40, and 89 seconds, respectively.
2	11.5	4.58×10^4 (estimated)	peak at 100 ms	0.05 cal/cm^2	--	Six animals exposed, four behind shutters and two unprotected. One of the unprotected animals received a minimal lesion. Location was 21,200 yards from ground zero in craft at undisclosed altitude.
	11.5	4.58×10^4	peak at 100 ms	0.0552 cal/cm^2	--	Six animals exposed, two behind inoperative shutter with 20% transmission, four unprotected. Three of the unprotected animals received minimal lesions. Location was on ground 17,600 yards from ground zero.
	10.3	1.29×10^5 (estimated)	peak at 100 ms	0.0833 cal/cm^2	--	Four humans and two animals located in a craft 19,360 yards from ground zero. All humans were protected by shutters (open transmission of 20%)which closed in 0.55 ms; no flash effects observed. Both animals were unprotected; one suffered a minimal lesion.

Table 4 (continued)

Ref.	Yield (KT)	Peak Luminance (mL)	Flash Duration (ms)	Total Energy at Corneal Plane	Pupil Diameter (mm)	Recovery Criteria and Procedures
2	10.3	1.29×10^5	peak at 100 ms	0.1052 cal/cm^2	--	Four humans and three animals at ground level 15,136 yards from ground zero. Humans were protected by shutters (see previous page) and were unaffected by the flash. Animals were unprotected and two of the three received minimal lesions.
	74.1	6.8×10^4	peak at 300 ms	0.0963 cal/cm^2	--	Six humans and three animals exposed in an aircraft 32,426 yards from ground zero. Three of the humans were protected by inoperative shutters (20% transmission); recovery times to 0.1 and 0.3 visual acuity were 72 and 90 seconds for one subject; times to read aircraft instruments with standard edge lighting and red flood lighting were 10-12 seconds for the other two subjects. The fourth subject's shutter closed in 0.55 ms and recovery was virtually instantaneous. Two subjects were behind sandblasted aircraft windows and required 90 seconds to recover to 0.1 visual acuity. Two of the three animals(all unprotected) received lesions.

Table 4 (continued)

	Yield (KT)	Peak Luminance (mL)	Flash Duration (ms)	Total Energy at Corneal Plane	Pupil Diameter (mm)	Recovery Criteria and Procedures
2	18.7	14.2×10^4	peak at 250 ms	0.0347 cal/cm^2	--	Six humans and four animals exposed at ground level 18,304 yards from ground zero. Two of the humans were behind shutters which closed in 0.55 ms and one subject was behind a shutter which closed in 0.9 ms. Recovery was instantaneous. Another subject was behind an inoperative shutter (20% transmission), behind a sandblasted diffuse window. Recovery took 6 seconds to read standard red-lighted aircraft instruments. The fifth subject was behind a sandblasted window, but without a protective shutter. Recovery to 0.1, 0.3, and 0.5 visual acuity required 20, 28, and 35 seconds, respectively. The sixth subject was behind a 20% narrow band filter and recovered immediately. None of the animals were protected and none received retinal lesions.

No dazzle or flash blindness were reported by any of the subjects. The authors concluded that during daylight, and at distances of a mile or more, there will be no significant dazzle effect from 1 to 5T nuclear bursts when observers are looking more than 90^{o} from line of sight to the burst. No data were presented regarding the absence or presence of reflecting sources, such as clouds.

These authors also cited data from the Ophthalmological Survey Group which studied the Hiroshima and Nagasaki casualties from which they cite that no case of flash blindness lasting more than about 5 minutes was reported. The authors also reviewed flash blindness reports from a number of previous observation experiments. A group of light-adapted subjects located in an aircraft at 15,000 ft, 9 miles from a low air burst (10-20KT) either looked directly at the flash or were oriented 180^{o} from the flash. Those who were facing away from the flash experienced no visual impairment, while those who viewed the flash directly had either no impairment or a temporary reduction in acuity ranging up to slightly less than 20/400, with complete recovery in less than 2 minutes. A United Kingdom report of flash blindness was also cited by Verheul et al. (41) in which results are presented on an observer who was blinded for two minutes at an altitude of 40,000 ft and 10 miles from detonation. He recovered useful vision in 5 minutes but the afterimage persisted for 12 hours. Since the observer's line of vision was about 25^{o} from the line of sight to the detonation, the afterimage was peripherally located. No other

information on the condition of exposure was given.

Comparison of laboratory experimental results with those of observations of nuclear detonations is difficult. Since appreciable thermal energy continues to be radiated after the minimum blink reflex time for atmospheric bursts greater than about 5-10KT, individual differences in blink response may influence the results. Those experiments in which shutters were employed provide results which are consistent with the laboratory findings. Whiteside's (24) data are in close agreement with the laboratory data, particularly if the nuclear exposure is considered of non-uniform intensity during the 100 millisecond exposure. Peak intensity would then be greater than 1.37×10^8 mL, a level at which there is some evidence of reduced efficiency of light in increasing recovery time (due to saturation of the visual pigments) during short exposures.

The minimum information about a weapon flash necessary for research and development purposes in regards to the problem of flash blindness is luminance, duration and visual angle subtended by the source whether it is a fireball or a surface illuminated by the fireball. The estimation of these parameters from information given in The Effects of Nuclear Weapons (1) have been discussed by Hill and Chisum (42). The thermal radiation from a nuclear weapon detonated at low altitude amounts to about 35% of the yield of the weapon. The other 65% is in nuclear radiation and mechanical energy. The ranges within which the latter two forms of energy are dissipated to safe levels are much shorter

than that for the thermal energy. The variation of the ranges with weapon yield is shown in Fig. 5, which was taken from Glasstone (1).

In their discussion Hill and Chisum (42) assumed that except for their eyes, personnel can be adequately protected up to the point at which they would receive second degree burns. On this basis they made use of the concept of equal effects of nuclear weapons regardless of weapon size. This concept is illustrated in Fig. 6 which was also taken from reference (1). At 0.1 mile from a 1KT weapon, or 10 miles from a 1 MT weapon, or anywhere to the left of the second degree burn line, the thermal and mechanical damage may well be so excessive that flash blindness is not a problem. The point at which flash blindness can become a problem is to the right of the second degree burn line. The second degree burn distance was arbitrarily defined as the minimum "safe" distance.

Hill and Chisum (42) constructed a luminance curve from blackbody luminance tables and fireball temperature as a function of time as shown in Fig. 7. The minimum safe distance for each weapon and an atmospheric transmission of 80% were used in these calculations. The luminances of the smaller weapons viewed at the minimum safe distances exceeded the luminance of the sun. The significance of these luminances for visual effects is more readily apparent from the integrated curves shown in Fig. 8 taken from reference (42). The integrated luminances which would be received by the eyes protected only by the blink reflex and by some of the protection devices under

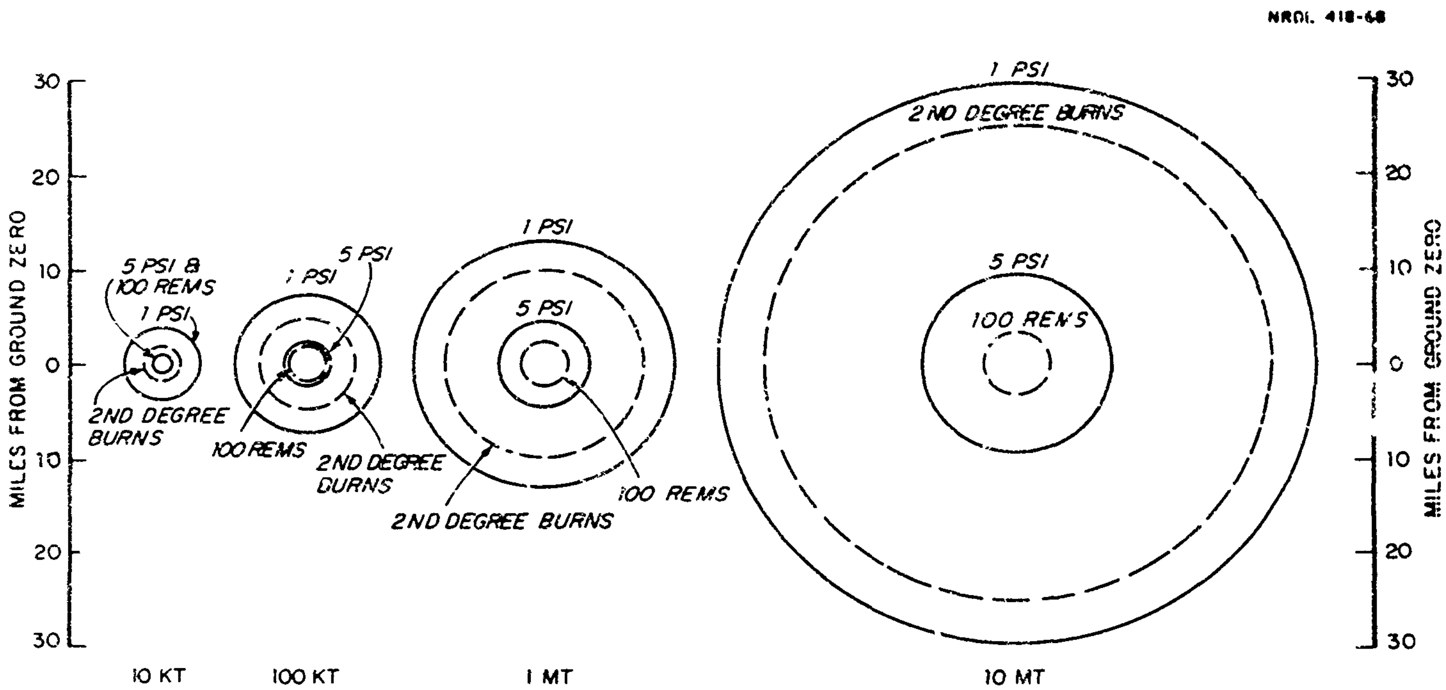

Fig. 5. Idealized ranges for effects of air burst with the heights of burst optimized to give the maximum range for each individual effect. From Glasstone' (p. 360).

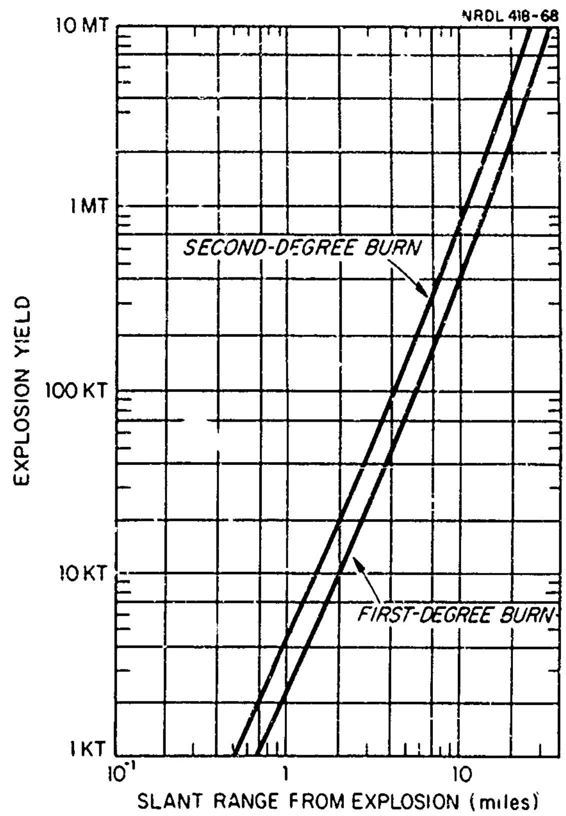

Fig. 6. Ranges for first- and second-degree burns as a function of the energy yield. From Glasstone[1] (p. 573).

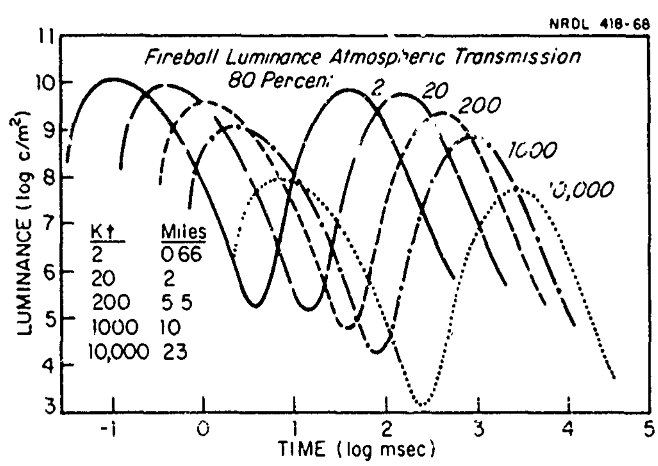

Fig. 7. Fireball luminance for five weapon yields at the minimum safe distance with 80 per cent atmospheric transmission.

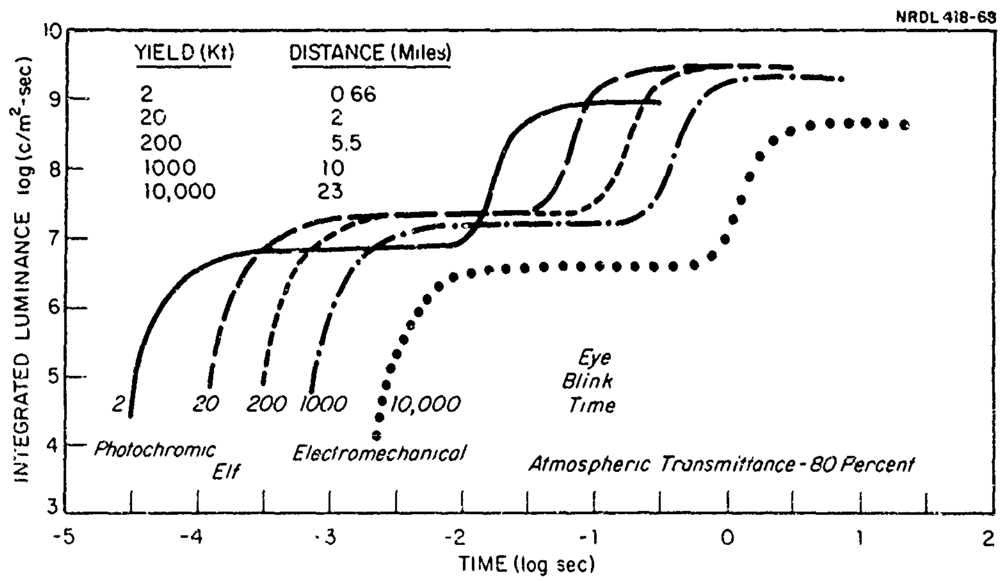

Fig. 8. Integrated fireball luminances for five weapon yields at the minimum safe distances with 80 per cent atmospheric transmission.

development are indicated along the abscissa. The intergrated luminance received with only the blink reflex as protection would be about equal to looking at the sun for one full second.

The extent of the retina covered by the image of a fireball will depend on the viewing distance as well as the fireball diameter, which is a function of yield and time. The relation of fireball diameter to yield and time is shown in Fig. 9 taken from reference (42). The fireball diameter at any specific time after detonation varies directly with weapon size. The visual angle subtended by a fireball when viewed at the minimum safe distance varies inversely with weapon size as shown in Fig. 10 taken from reference (42). As the fireball diameter increases, the retinal image size increases. This increase in image size stimulates new areas of the retina. Only the retina at the center of the image receives the full extent of the fireball luminance.

In the event that the fireball itself is not imaged on the retina, other surfaces within the visual field will be illuminated by the fireball. For this reason it is important to know how much illumination a fireball can produce. The illumination received at the minimum safe distance can be determined from the fireball luminance and diameter, viewing distance and atmospheric transmission. This relation is shown in Fig. 11, taken from reference (42). The luminance of a surface with a diffuse reflectance of 10% is shown on the right ordinate scale. Integration of the illumination and resulting luminance is shown in Fig. 12.

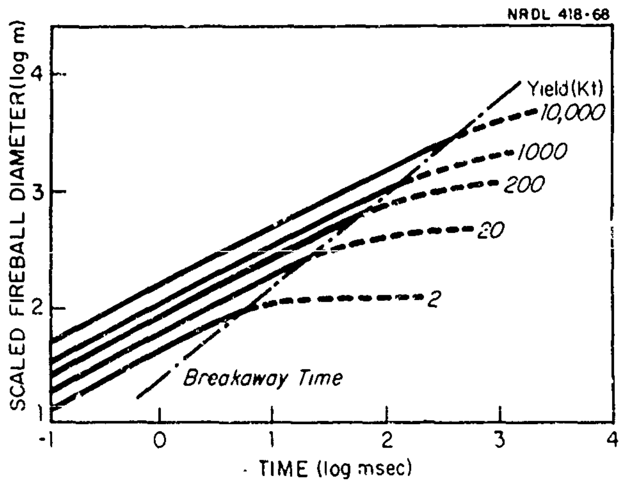

Fig. 9. Fireball diameters for five weapon yields.

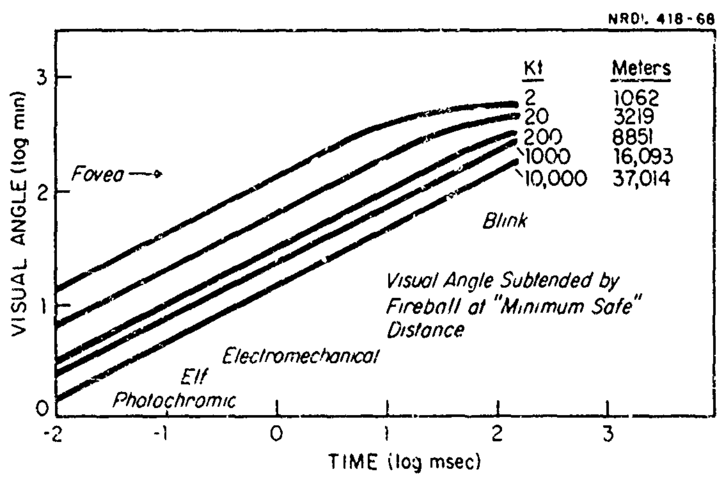

Fig. 10. Visual angles subtended by the fireball of five weapon yields at the minimum safe distances.

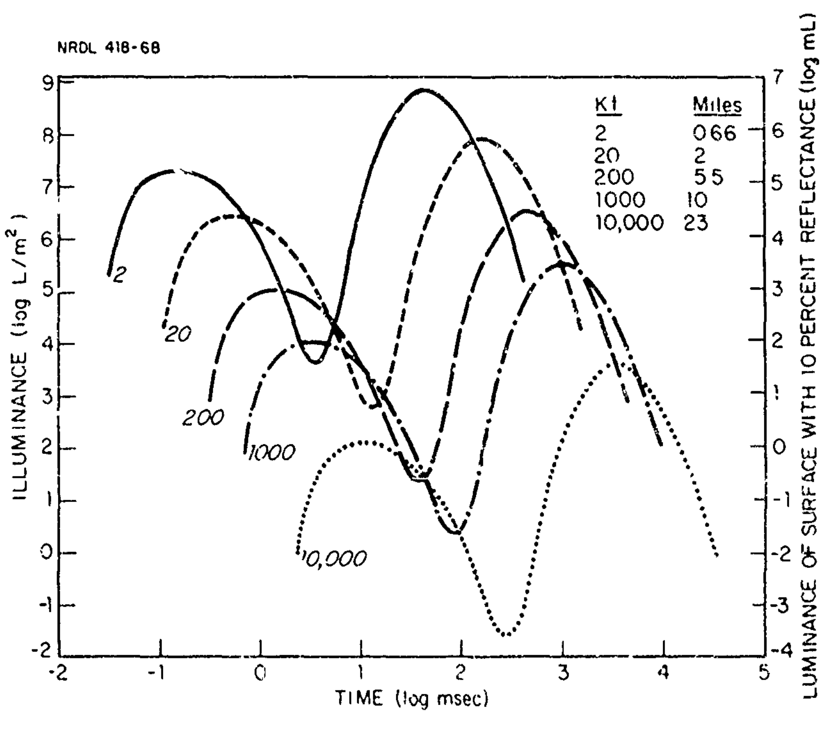

Fig. 11. Fireball illuminances for five weapon yields at the minimum safe distances and luminances of a 10 per cent reflecting surface at 80 per cent atmospheric transmission. (From Hill and Chisum (42)).

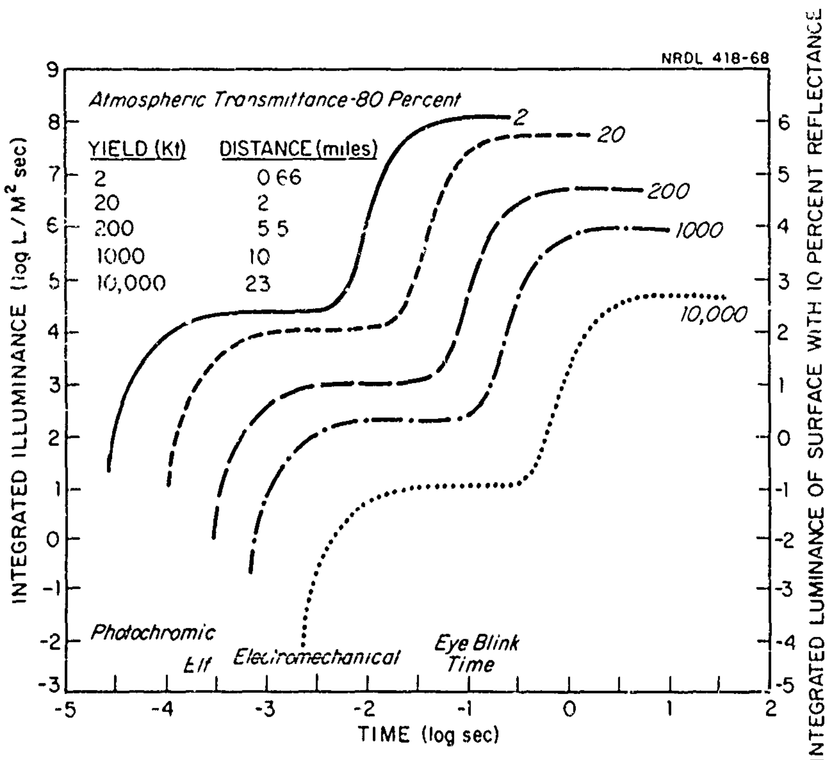

Fig. 12. Integrated fireball illuminance for five weapon yields at the minimum safe distances and integrated luminance of a 10 per cent reflecting surface at 80 per cent atmospheric transmission.

The integrated luminance received from a surface with 10% diffuse reflectance can be over 5 log mL-sec if no protective measures but the blink reflex is used. This luminance is sufficient to cause flash blindness hazardous to a pilot. From these curves, Hill and Chisum (42) point out that it is readily apparent that for low altitude detonations at the minimum safe distances the eyes can receive more than 5 log mL-sec of visible energy from a 10% reflector before there is time to blink, and the luminance of a fireball viewed directly can be as much as four orders of magnitude greater.

Hill and Chisum (42) surmised the dangers of eye damage from high altitude detonations from a qualitative comparison of the rates of emission for high and low altitude bursts shown in Fig. 13 taken from reference (1). They pointed out that the total thermal energy for high altitude bursts is 70% of the weapon yield as compared to 35% of low altitude bursts, and the rate of emission is also many times greater.

As pointed out by Hill and Chisum (42), the predictions of luminances presented in their discussion should be considered merely as guidelines. Other factors not considered such as altitude of detonation, terrain, atmospheric and meterological conditions are required for prediction of flash luminances in operational situations. With reasonable knowledge of the luminance personnel may be expected to encounter in operational situations, adequate flash blindness protection possibly may be devised, and the minimum safe distance for personnel will not have to be extended.

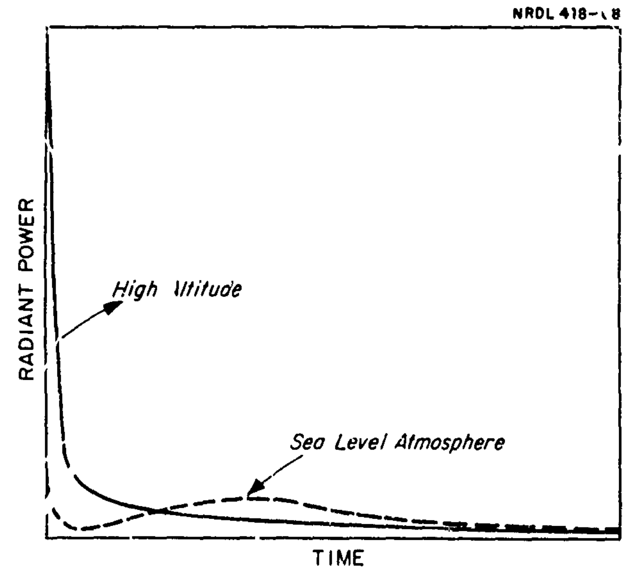

Fig. 13. Qualitative comparison of rates of arrival of thermal radiation at a given distance from high-altitude and sea-level bursts. From Glasstone' (p. 81).

5. Summary and Conclusions.

5.1. Summary. Published data on flash blindness from field tests and laboratory experiments have been summarized. The laboratory research results are presented for both low and high intensity flashes. A number of reports on low intensity flashes are referenced in this report with little discussion since the studies generally employed bleaching light intensities much lower than may be produced by nuclear weapons. However, observations of the effects of lower intensity flashes may help in understanding higher intensity phenomena. Results of low light intensity experiments on the effect of age on dark adaptation and critical flicker fusion frequencies showed that in flicker as well as in dark adaptation, the increase in threshold luminance is not a linear function of age, but that at about the age of 40 a sudden acceleration in sensitivity to glare occurs.

A relationship was obtained from 194 cases (20 to 60 years of age) which states that for every increase of 13 years in age, intensity of illumination must be doubled to be just seen by the fully dark adapted eye.

On the basis of experiments employing high light intensity, it was concluded that recovery times depend upon total effective integrated energy in the flash, the size of the pupil, the state of adaptation prior to the flash, the size of the critical detail in the recovery target, the luminance of the target, the spectrum of the radiation and individual variation in response. The results of various studies are listed below:

1. The only portion of flash radiation that influenced the recovery times for foveal performance was in the visible region. Infrared had no effect on prolonging the recovery time following the flashes, even when it accounted for more than 50% of the total flash energy.

2. There was a small but statistically significant effect on foveal recovery for different flash-field diameters for 2.5° to 10°, with the smaller fields producing longer recovery times.

3. An approximately linear relationship was found between the logarithm of retinal illuminance times the duration of the flashes and logarithm of the recovery times for the recognition of a 20/60 acuity target at [illegible] millilambert, over the range of 20 seconds to 130 seconds recovery time, corresponding to a range of 9×10^5 to 3×10^7 troland-seconds flashes.

4. There was no significant cumulative effect on recovery times with successive flashes after the second flash when they were presented at intervals of three or four minutes. The first flash in a series produced a slightly shorter recovery period than the following flashes.

5. The recovery times following a flash depend upon the type of target used for measuring visual performance. There was a linear relationship between the logarithms of the recovery time and the visual acuity for different size test letters, expressed as the reciprocals of the visual angle subtended.

6. The variation between individuals exposed to flash was found to be large. There was a factor of about 2 between the means of the highest recovery time and lowest recovery time.

7. There is some indication that vision through na[illegible] spectral band eye-protective filters may be possible [illegible] the eye's sensitivity in other spectral regions is [illegible]ly preserved after intense flash. [illegible] to extend the findings to various wavele[illegible] already considered and to different durations of [illegible]pting stimuli, covering the range up to those intensities that produce irreversible retinal disorder.

An examination of data from field experiments led to the conclusion that since appreciable thermal energy continues to be radiated after the minimum blink reflex time, for atmospheric bursts greater than about 5-10KT, individual differences in blink response may influence the results. Those experiments in which shutters were employed provide results that are consistent with the laboratory findings. As in the laboratory experiments, considerable variation in recovery between subjects was found. In addition, variation in recovery was found in the same individual from one test to another under comparable conditions.

The minimum information about a weapon flash necessary for research and development purposes in regards to the problem of flash blindness appears to be luminance, duration and visual angle subtended by the source whether it is a fireball or a surface illuminated by the fireball. A discussion of the estimation of these parameters from information given

in Effects of Nuclear Weapons (1) is presented. From the estimates presented it appears that the integrated luminance received from a surface with 10% diffused reflectance from a 5-10KT low altitude burst can be over 5 log mL-sec if no protective measures but the blink reflex is used. This luminance is sufficient to cause flash blindness hazardous to pilots. The luminance of a fireball viewed directly can be as much as four orders of magnitude greater.

From a military operational point of view, the conclusion that can be drawn from this survey is that any further investigation on the flash blindness problem should be justified in terms of studies designed to develop protective devices based on the findings which indicated that sensitivity might be preserved in parts of the spectrum, while permitting continuous viewing through special eye-protective filters. Experiments designed to refine the results of basic phenomena already published do not seem justified.

5.2. Conclusions. The most important variables which affect the time of recovery from flashblindness following intense flashes of light are (1) intensity of the flash, (2) duration of the flash, (3) size of the test object (recovery target), (4) luminance of the test object, (5) pupillary size, (6) age of the subject, (7) individual response amongst the subjects and (8) spectrum of the flash.

The review of the research on these variables presented in the text of this report with ample references indicates that the treatment of these variables is adequate for the purposes of military operational

situations with the exception of the treatment of spectral effects on recovery time. It appears that further research is required to extend the findings of the studies on spectral effects to various wavelengths not already considered and to different durations of adopting stimuli, covering the range up to those intensities that produce irreversible retinal disorder.

Finally it can be concluded that any further investigation on the flash blindness problem should be justified in terms of studies designed to develop protective devices, specifically including devices based on findings which indicated that sensitivity might be preserved in parts of the spectrum, while permitting continuous viewing through special eye - protective filters.

6. Glossary.

6.1. Candle. (1) The unit of luminous flux. One candle is defined as the luminous intensity of 1/60 square centimeter of a black body radiator operating at the temperature of solidification of platinum. (2) The older unit, the international candle, is a specified fraction of the average horizontal candle power of a group of carbon-filament lamps preserved at the National Bureau of Standards.

6.2. Candle Power. Luminous flux expressed in candles.

6.3. Lambert. A unit of luminance equal to $1/\pi$ candle per square centimeter, and, therefore, equal to the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of one lumen per square centimeter.

6.4. Lumen. The unit of luminous flux. It is equal to the flux through a unit solid angle (steradian) from a uniform point source of one candle, or to the flux on a unit surface all points of which are at unit distance from a uniform point source of one candle.

6.5. Luminance. The luminous flux per unit solid angle emitted per unit emissive area as projected on a plane normal to the line of sight. The unit of luminance is that of a perfectly diffusing surface giving out one lumen per square centimeter and is called the lambert.

6.6. Luminous Flux. The time rate of flow of light. When radiant flux is evaluated with respect to its capacity to evoke the brightness attribute of visual sensation, it is called luminous flux, and this capacity is expressed in lumens.

6.7. Lux. The M.K.S. unit of illuminance equal to one lumen per square meter.

6.8. Illuminance. The density of the luminous flux on a surface; it is the quotient of the flux by the area of the surface when the latter is uniformly illuminated.

6.9. Illuminance, Retinal. A psychophysiological quantity, partially correlated with the brightness attribute of visual sensation and measured in trolands.

6.10. Nit. A unit of luminance, equal to 1 candle per square meter.

6.11. Troland. A unit of retinal illuminance, being the visual stimulation resulting from an illumination of 1 candle per square meter when the apparent area of the entrance pupil of the eye is 1 square millimeter.

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13. ABSTRACT

The nature and cause of flash blindness are briefly discussed, and the most important data from both field tests and laboratory experiments are summarized. Data on time of recovery from effects of flash blindness are reviewed and presented as a function of total effective integrated energy in the flash, the size of the pupil, the state of adaptation prior to the flash, the size of the critical detail in the recovery target, the luminance of the target, the spectrum of the radiation, and individual variation in response.

From a military operational point of view, this survey indicates that there is sufficient data on basic phenomena to proceed to research on possible countermeasure devices.

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